EVALUATION OF PREDICTIVE METHODS FOR INSTRUCTURE SHOCK WAVE PROPAGATION

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ABSTRACT

The analysis of explosively-generated shock wave propagation through enclosed structures is of particular interest to engineers concerned with structural blast responses. Accurate predictions of peak pressure and impulse values are often difficult to generate analytically due to various complications inherent in modeling complex structures. Several tools, based on empirical data, exist that aid the engineer in quickly scoping airblast propagation, but these require many simplifying assumptions that may invalidate the results.

Three predictive methods, one analytical, one computational, and one experimental, were used in this study to analyze blast propagation through a predefined, semi-enclosed structure. Expected blast pressure data were determined for the specific case of an explosive charge detonating above an opening in the structure at a series of locations on the structure .

BlastX, a simple airblast prediction tool developed by the US Army Engineer Research and Development Center, analytically predicts pressure time-history data for specific user-defined locations within a fully-enclosed, predefined space or series of spaces based primarily on empirical fits [1]. CTH, an advanced hydrocode developed by Sandia National Laboratories for the purpose of modeling materials under large deformation, was used for high-fidelity analyses of shock propagation through the structure [2]. Finally, a 1/8th-scale model of the structure was constructed. Scaled explosive charges were used to gather blast pressure data at locations coincident with the analytical and computational models. These experimental data were then compared to the other two methods, and the results are presented herein.

The focus of this paper is to evaluate the analytical and computational predictive methods described above—including the required simplifying assumptions, strengths, and limitations of each—by comparing the results of their respective analyses of the same target structure, and by comparing those results to empirical data gathered from a 1/8th-scale experiment using the structure in question.

OBJECTIVE

The ability to predict explosively-generated shock wave propagation through enclosed structures is of particular interest to military structural engineers. Accurate predictions of peak pressure and impulse values are often difficult to generate analytically due to various complications inherent in modeling complex structures. Several analysis tools exist that are based on empirical data aid the engineer in quickly scoping airblast propagation, but these require many simplifying assumptions that may invalidate the results. On the other hand,

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14. ABSTRACT

The analysis of explosively-generated shock wave propagation through enclosed structures is of particular interest to engineers concerned with structural blast responses. Accurate predictions of peak pressure and impulse values are often difficult to generate analytically due to various complications inherent in modeling complex structures. Several tools, based on empirical data, exist that aid the engineer in quickly scoping airblast propagation, but these require many simplifying assumptions that may invalidate the results. Three predictive methods, one analytical, one computational, and one experimental, were used in this study to analyze blast propagation through a predefined, semi-enclosed structure. Expected blast pressure data were determined for the specific case of an explosive charge detonating above an opening in the structure at a series of locations on the structure . BlastX, a simple airblast prediction tool developed by the US Army Engineer Research and Development Center, analytically predicts pressure time-history data for specific user-defined locations within a fully-enclosed, predefined space or series of spaces based primarily on empirical fits [1]. CTH, an advanced hydrocode developed by Sandia National Laboratories for the purpose of modeling materials under large deformation, was used for high-fidelity analyses of shock propagation through the structure [2]. Finally, a 1/8th-scale model of the structure was constructed. Scaled explosive charges were used to gather blast pressure data at locations coincident with the analytical and computational models. These experimental data were then compared to the other two methods, and the results are presented herein.

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more advanced computational methods require advanced training, tools, and resources that are often not readily available. Therefore, the objective of this research effort will be the results of analyses of three predictive methods, one experimental, one analytical, and one computational model, to analyze blast wave propagation through a predefined, semi-enclosed structure.

Expected blast pressure data were determined at a series of locations on the structure for the specific case of a bare explosive charge detonating above an opening in the structure. The validity of simplifying assumptions required for each method is discussed.

BlastX, a simple airblast prediction tool, derives pressure time-history data for specific user-defined locations within a fully-enclosed, predefined space or series of spaces based primarily on empirical fits [1]. BlastX uses ray tracing and empirically derived rules for combining direct and reflected shock waves to construct complicated shock waveforms. CTH, an advanced hydrocode developed by Sandia National Laboratories for the purpose of modeling materials under large deformations, was used for high-fidelity analyses of shock propagation through the structure [2]. Two CTH models were considered: a simple model containing no interior beams or purlins, and a complex model that more accurately represented the structure in question by incorporating interior structural members. Finally, a 1/8th-scale model of the structure in question was constructed. Scaled explosive charges were used to gather blast pressure data at locations coincident with the analytical and computational models, and these experimental data were used as baselines for comparisons with the other two methods.

METHODOLOGY

<u>Scenario</u>

The structure considered in this evaluation is a canopy consisting of a roof deck suspended 5 ft above a ceiling deck, forming an attic space in-between. The construction is a typical steel frame and purlin building with 1-on-12 roof slope. The sides of the attic space are enclosed, while the ends (gables) are open to the atmosphere (see Figs. 1 and 2).

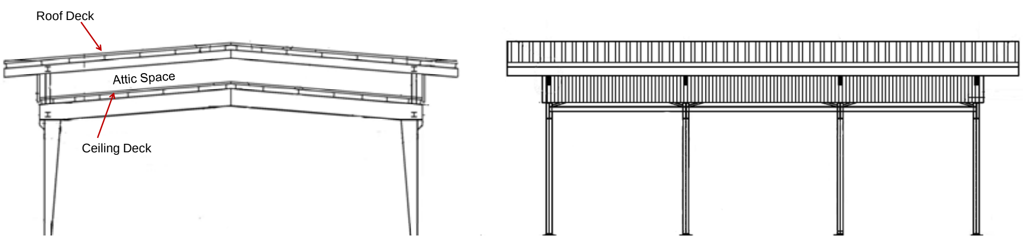

Figure 1. End and Side Elevation Views of Structure.

Blast pressures were predicted or measured for all three methods at the specific locations noted in Fig. 2 for the scenario of a spherical bare charge (~50 lb TNT), centered over a 9-ft-diameter opening, with the bottom of the charge flush with the roof line.

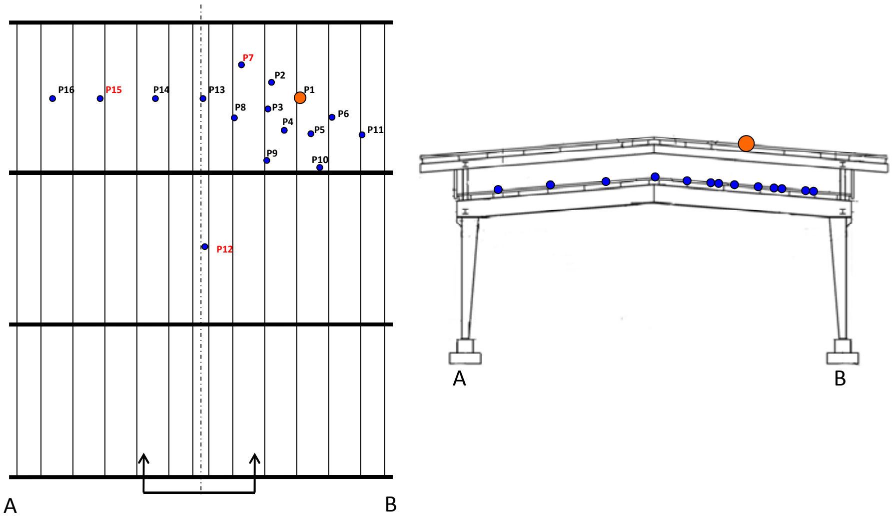

Figure 2. Plan and Elevation View of Gage Layout.

(Target locations discussed in Results Section shown in Red)

Scale Model

A 1/8th-scale model was constructed of steel. Cross sections of structural members were simplified by using rectangular cross sections of the same outer dimension in place of complex shaped members (I-beams, Z-shaped purlins), etc. All scaled dimensions are typical of this type of metal building construction; however, the material properties are not, thus the model was strengthened to be non-responding. The sole purpose of the scale model was to collect blast pressure data as the shock front propagates and reflects throughout the confined attic space. Photographs of the scale model are shown in Fig. 3.

Figure 3. Elevation and Plan View of Instrumented Scale Model, Showing a Scaled 3-ft Opening.

BlastX Model

The BlastX model consisted of a 6-sided room representing the “attic space” discussed in the previous section. The slope of the roof/ceiling decks was not modeled for simplicity. A spherical charge was used in this case as well. BlastX cannot model complex shapes (purlins, frames, beams) within the structure, so the inside of the attic space was smooth. The three dimensional depiction of the BlastX model is shown in Fig. 4.

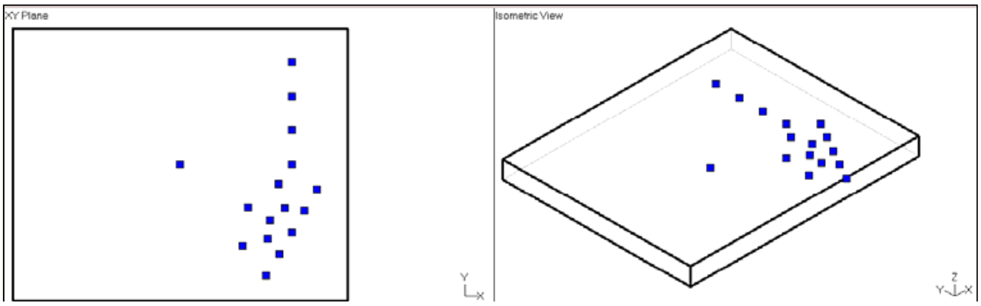

Figure 4. Plan and Isometric views of BlastX model.

(Pressure target locations shown in blue)

CTH Model

The CTH model incorporated the upper portion of the scaled model. Two CTH models were considered. First, for simplicity, purlins, frames, and beams inside the attic space were ignored. In the second (complex) CTH model, frames and purlins were incorporated in order to determine their effect on the blast propagation. Fig. 5 shows three-dimensional views of the models with the spherical charges over the openings. In both cases, the Jones-Wilkins-Lee equation of state was used to model the charge, and the structure's material used a SESAME tabulated equation of state with a simple elastic-plastic model for mild steel. The Jones-Wilkins-Lee equation-of-state parameters are listed in Table 1. Air was also included using the SESAME tabulated equation of state in CTH in order to properly propagate the shock wave through the structure. Tracer particles were placed in the same target locations as the scaled model shown in Fig. 2 to record pressure time-histories throughout the simulation.

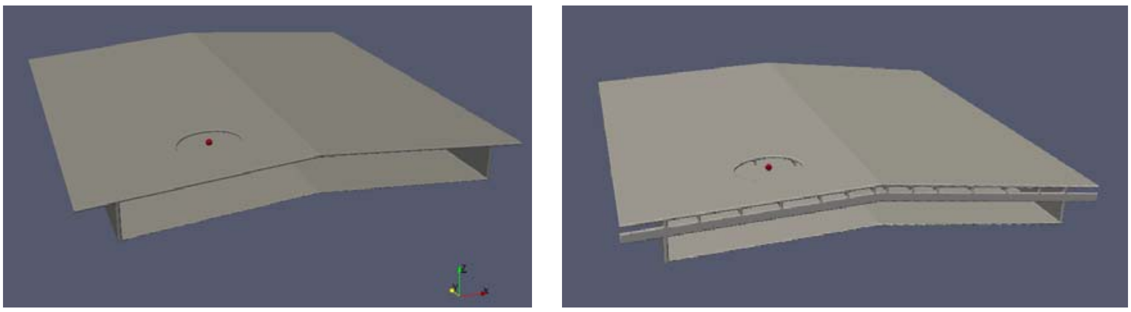

Figure 5. Isometric Views of Simple (left) and Complex (right) CTH Models.

Table 1. JWL parameters used for modeling the explosive.

Constant	Value	Constant	Value
R0 (lb·ft^{-3})	99.95	TJC (°F)	5657
T0 (°F)	76.73	E0 (Btu)	8.536
AG (psi)	8.84E+07	ESFT (Btu)	5.527
BG (psi)	1.88E+06	DCJ (ft·s^{-1})	26880
R1	4.5	PCJ (psi)	4.06E+06
R2	1.4		
WG	0.25		
CV (Btu·lb^{-1}·°F^{-1})	0.1653		

RESULTS

Results of both the analytical and computational methods were adequate in terms of broadly scoping the effect of the airblast propagation through the structure. However, significant differences were noted: generally, BlastX underestimated initial peak pressures, sometimes by as much as 50%, while CTH tended to overestimate peak pressures across the board, sometimes more than 100% higher. Both methods have greater difficulty predicting peak pressures at target locations near the detonation, but accuracy improved with distance from the charge. Due to the large scope of the experiment, only the results from a few target locations will be discussed.

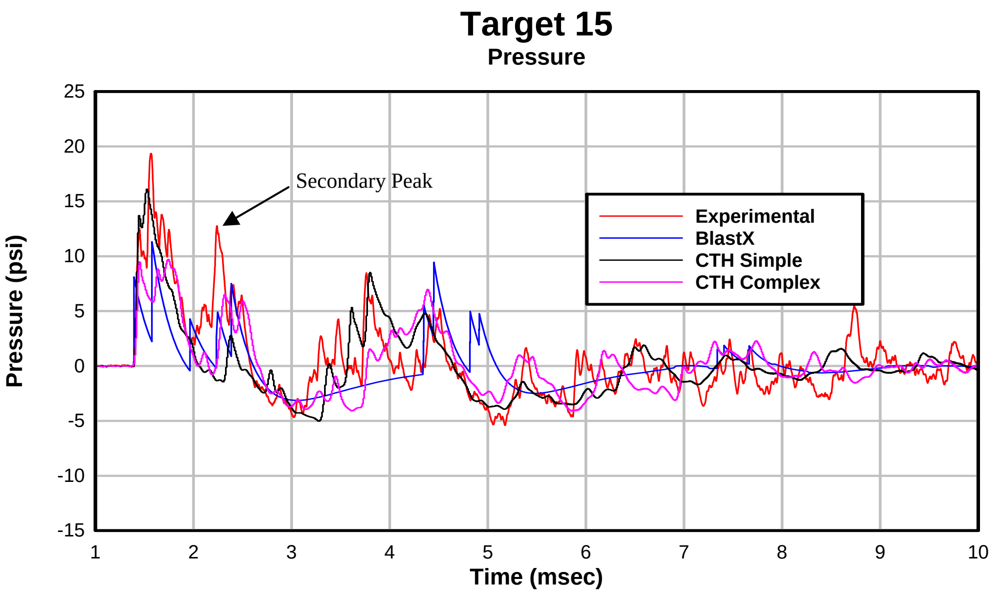

Figure 6. Pressure Time History at Target 15.

Predictions for Target 15 (Fig. 6) were typical of those gages farther from the charge. The BlastX predictions underestimated the peak pressure values, although the general waveform was relatively accurate, especially at early times (<4 msec). The simple CTH predictions followed the experimental results more closely early on, while the complex model tracked the experimental results more closely in late time. Neither the CTH models nor the BlastX method accurately matched the secondary peak magnitude shown in Fig. 6 at 2.25 msec. This secondary peak was generally evident in all target locations.

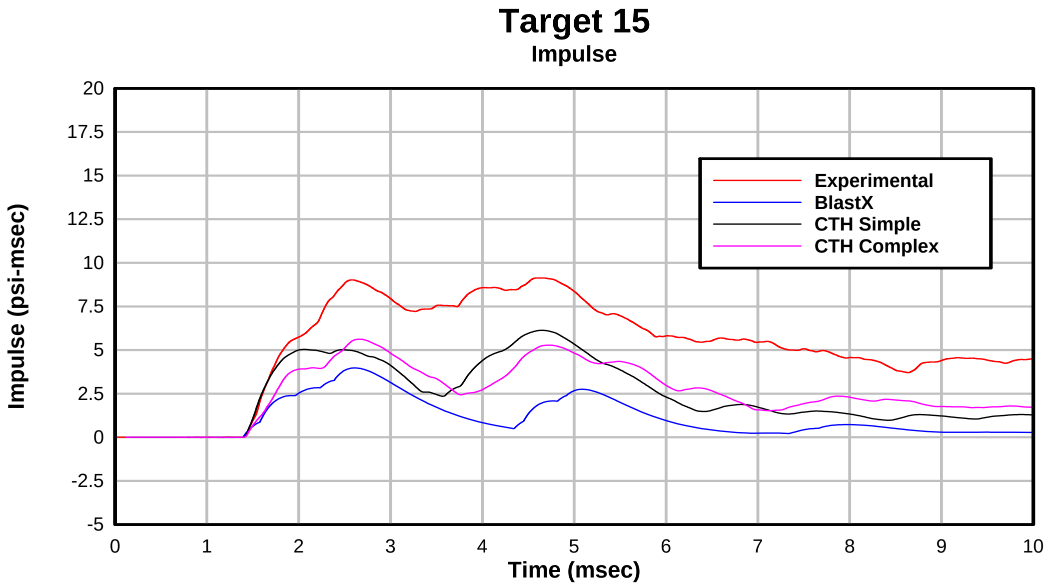

Figure 7. Impulse Time-History at Target 15.

The impulse-time history for Target 15 is also typical of most targets. BlastX and CTH both underestimated the overall impulse; however, the waveforms generally match the experimental results. The primary cause for the discrepancy between computational and experimental impulse values is the secondary peak at 2.25 ms (see Fig. 6). It is after this time that the primary divergence in impulse values occurs.

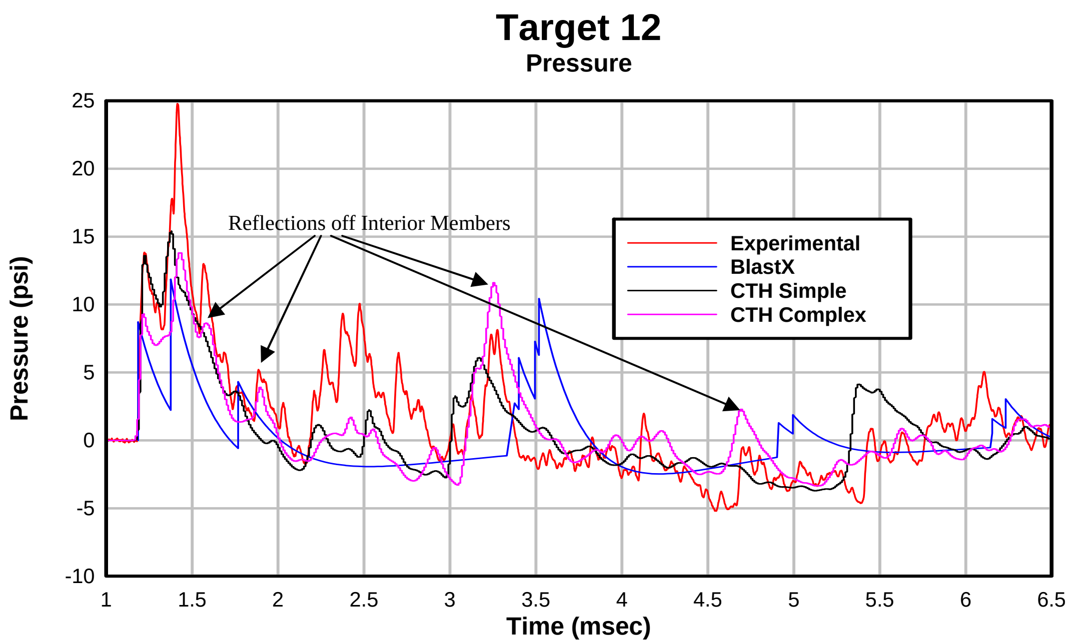

Figure 8. Pressure Time-History for Target 12.

At Target 12, CTH predicted the early-time response almost identically to what was measured in the experiment. Most of the late-time pressures were also tracked in the numerical model. The same secondary rise in the experimental data highlighted in Fig. 6 is also evident here but is much longer in duration. This secondary rise was detected in the CTH model, but again the magnitude is in error (too low). This error affects the overall impulse from the numerical model, which would otherwise match the experimental data much more closely. Interestingly, while the complex CTH model underestimates the early-time response, several smaller pressure peaks (Interior Member Effects, Fig. 8) are evident in later time that clearly coincide with similar peaks in the experimental results. At this medium range from the charge, the complex CTH model more accurately represents the pressure field both in magnitude and waveform.

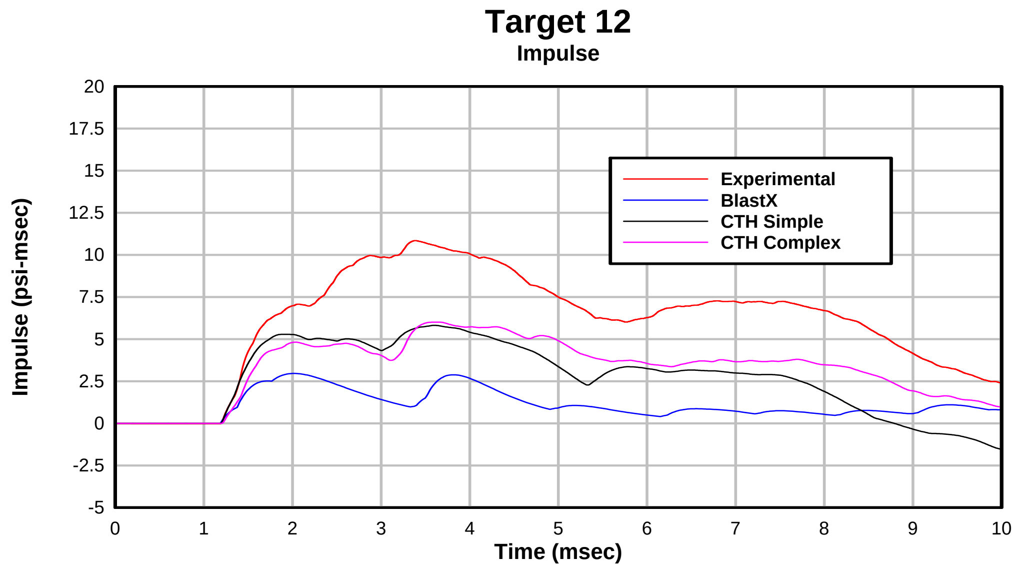

Figure 9. Target 12 Impulse Time-History.

The impulse responses for Target 12 reflect the absence of the long duration, secondary peak from Fig. 8. As a result, the peak impulses of both CTH models are, at best, only half of what the experimental model produced. It should also be noted that while the simple CTH model nearly mirrors the experimental results (albeit at a lower magnitude), the BlastX results diverge significantly starting around 5 msec and are significantly in error in terms of magnitude.

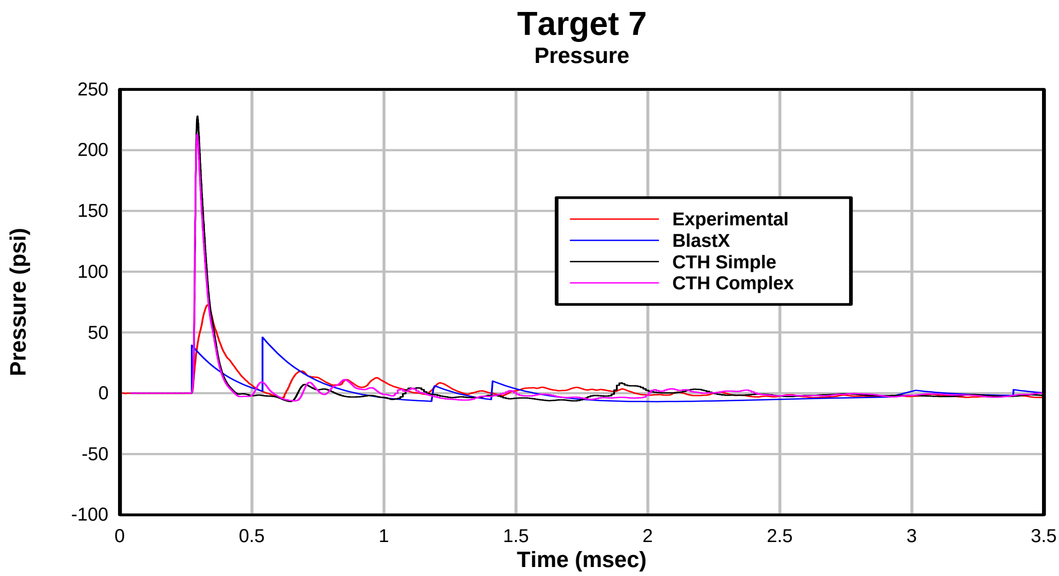

Figure 10. Target 7 Pressure-Time-History.

Data from Target 7 were selected as the worst case for predictions not matching the experimental results. The CTH models grossly overestimate (by 200%) the peak pressure of the experimental model. However, the late-time reflections are more accurate. CTH continues the trend of generally matching the shape of the secondary peak, but miscalculates the magnitude. BlastX significantly under- and over-predicts the first and second peaks, respectively.

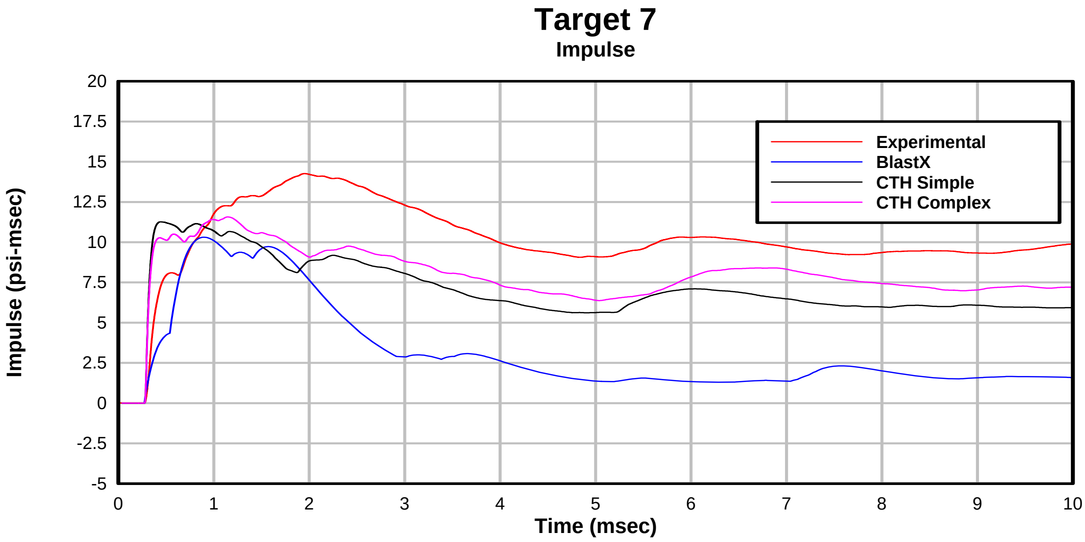

Figure 11. Target 7 Impulse Time-History.

Again, as in previous targets, late-time reflections cause the overall impulse of the experimental model to be greater than that of either the analytical or computational models.

One of the advantages of performing computational simulations is the ability to investigate phenomena that cannot be captured due to limitations of experimental measurement. Fig. 12 shows pressure contours of the center cross section of the structure (Target 12) at various early times from the two CTH simulations. Inside the attic space, two waves can be seen converging toward the center at the ceiling deck.

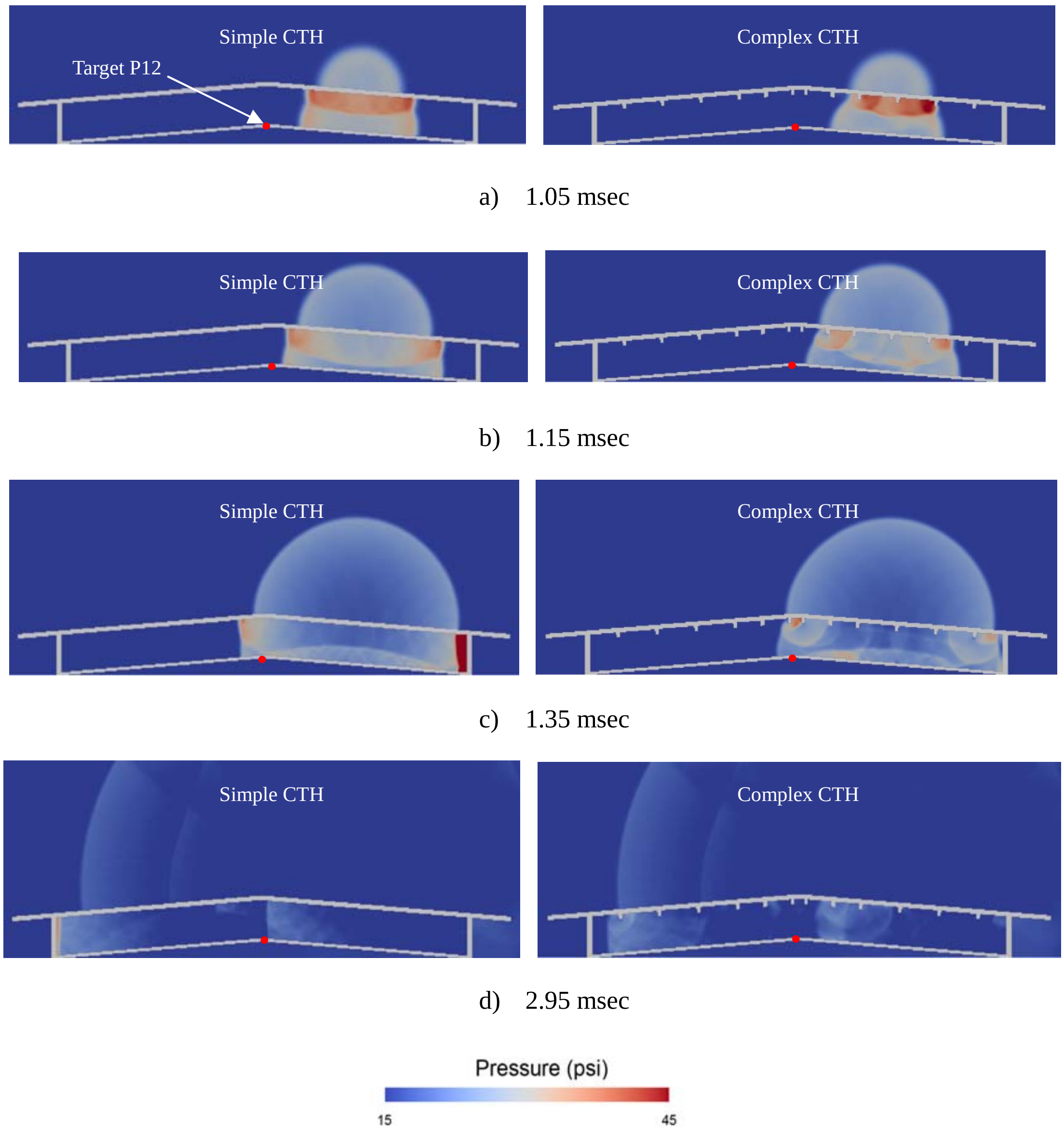

Figure 12. Pressure Contours at Various Times from Simple and Complex CTH Models.

Fig. 12 shows the effect that the additional reflecting surfaces have on the in-structure blast event. At 1.05 msec (Fig. 12. (a)), we see that the blast wave has already been significantly hindered by the presence of the lateral purlins. The progression of the secondary shock wave is slowed, and its magnitude is decreased at Target 12 as a result. In Fig. 12 (c), we see that the secondary shock has already arrived at Target 12 for the simple model, while it has not progressed as far in the complex model, and an additional reflection from the purlins is converging on the target as well. This is evident in Fig. 13 where at time "c", the simple model has already captured the secondary peak, yet the complex model's secondary rise does not occur for another 100 microseconds.

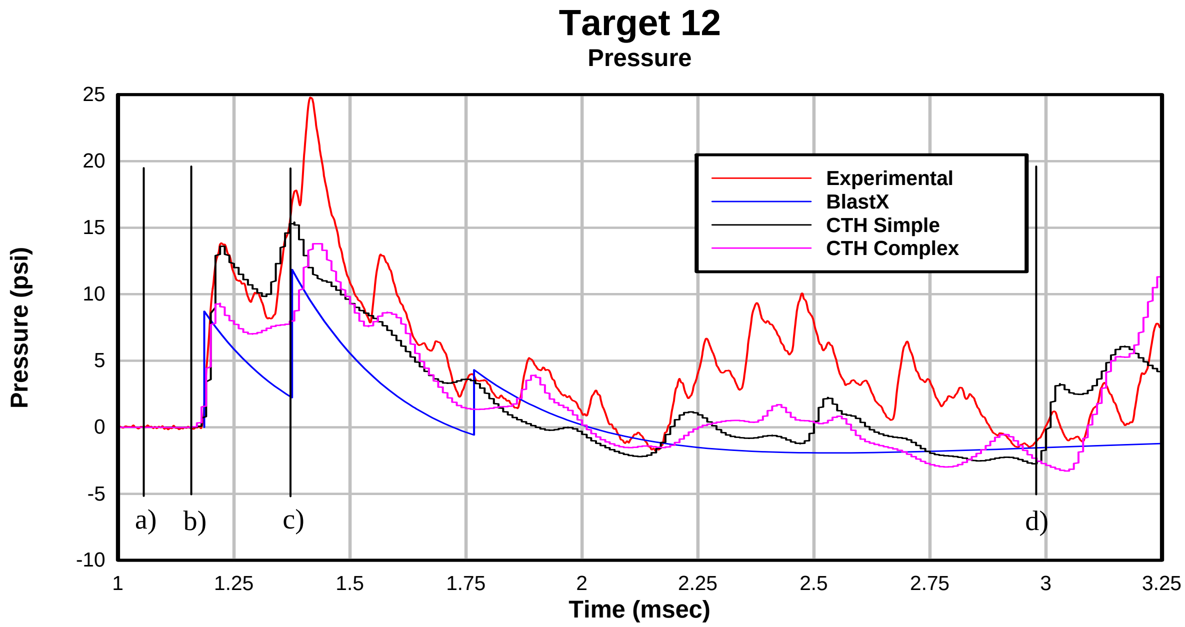

Figure 13. Closeup of Target 12 Results, CTH Pressure Contour Locations (Fig 12) Noted.

CONCLUSIONS AND RECOMMENDATIONS

For the scenario presented here, the CTH models more accurately represent the actual scenario baselined by the 1/8th-scale model. However, the resources and effort required may not justify the use of CTH in all cases.

The complex CTH model generally overestimates the effects of purlins and beams on blast propagation at early times as opposed to the simple model but produces a much more realistic picture of late-time reflections.

BlastX is a useful tool for quickly scoping the expected pressures within a structure; however, it does not model the blast environment to the same degree of accuracy as does CTH.

CTH not only provides a higher fidelity model of the blast environment in this case, it also provides the structural engineer with visual representations of the blast propagation, which enable designers to consider airblast in the initial design (see Fig. 12).

This initial effort is a baseline that should be extended to predict the blast environment within a responding structure.

ACKNOWLEDGEMENTS

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